Probing the EoS of Asymmetric Matter

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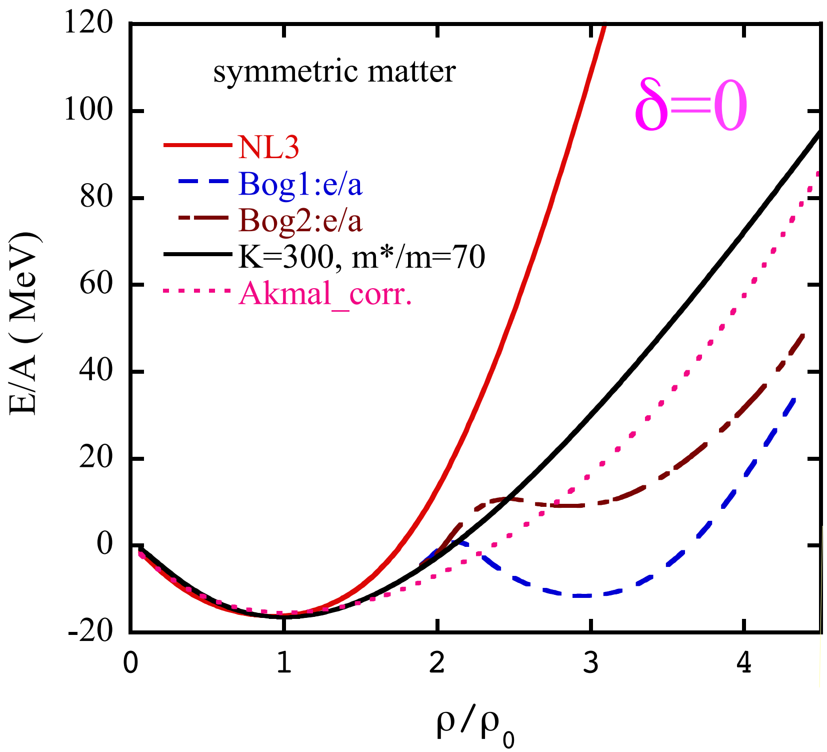
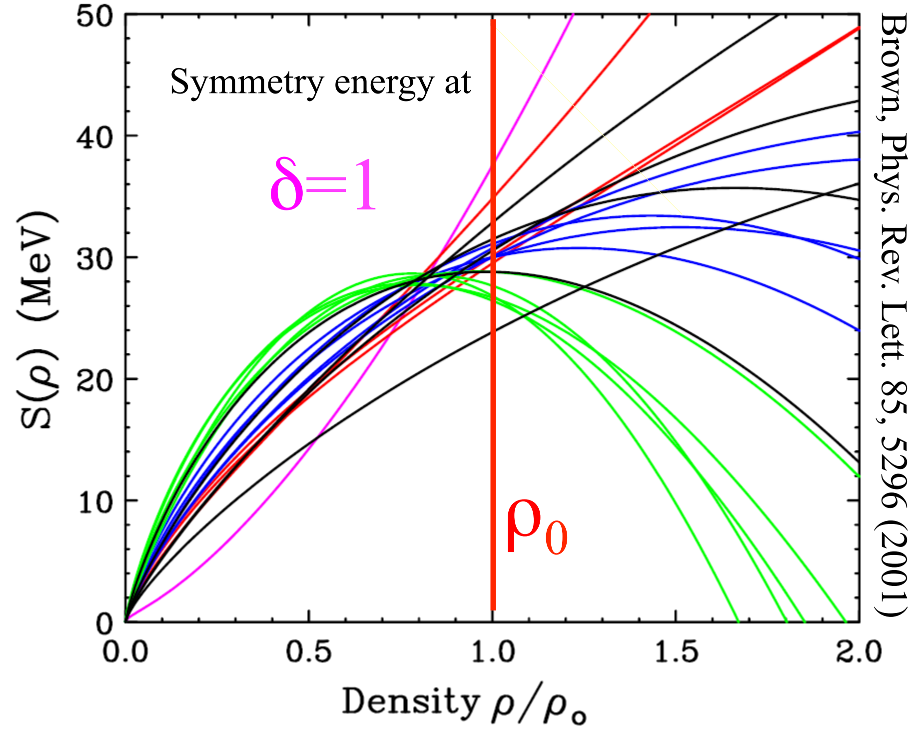
- Motivations
- Sources of constraints on the EOS and symmetry energy.
  - Astrophysics
  - Nuclear experiments
- Laboratory constraints from nuclear collisions
- Cross comparison of present constraints and experimental outlook

EoS: How does it depend on ρ and δ?





$$E/A\,(\rho,\delta) = E/A\,(\rho,0) + \delta^2 \cdot S(\rho)$$

$$\delta = (\rho_n - \rho_p)/\,(\rho_n + \rho_p) = (N-Z)/A$$

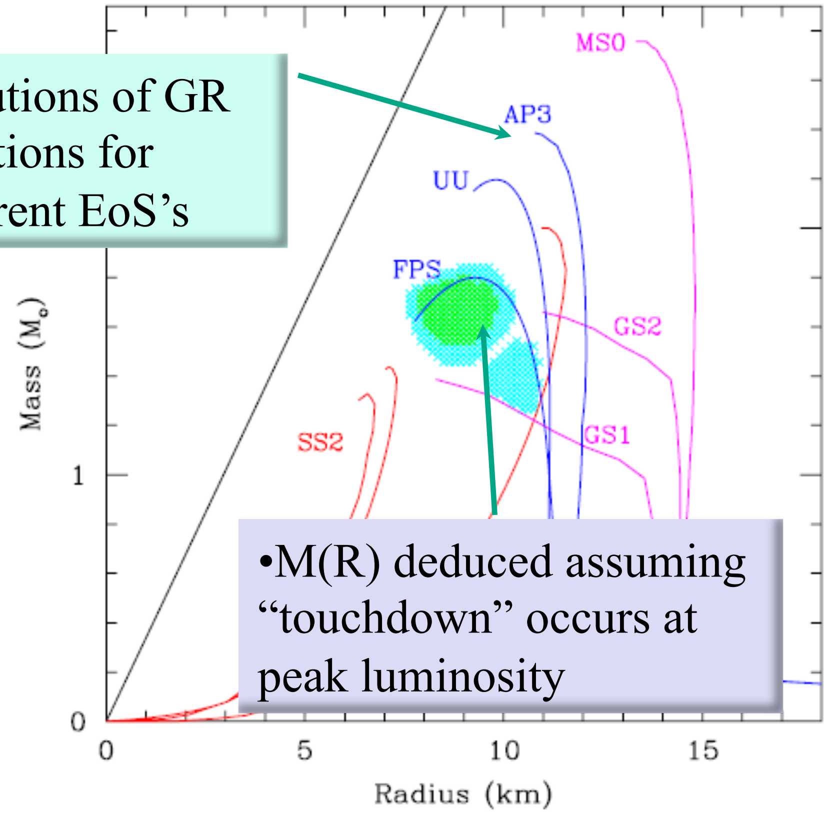
$$P = \rho^2 \left.\frac{\partial (E/A)}{\partial \rho}\right|_{s/a}$$

- Symmetry energy calculated here with effective interactions constrained by Sn masses
- This does not adequately constrain the symmetry energy at higher or lower densities

EOS, Symmetry Energy and Neutron Stars

- Symmetry energy influences:
  - Neutron star stability against gravitational collapse
  - Stellar density profile
  - Internal structure: occurrence of various phases.
- Observational consequences:
  - Cooling rates of proto-neutron stars: D. Yakovlev et al, Phys.Rep 354, 1 (2001)
  - Torsional oscillations in Magnetars. A. Watts et al., ApJ. Lett. 637, L117.
  - Stellar masses, radii and moments of inertia.
    - Has been studied by analysis of time dep. of X-ray burst luminosities, spectral temperatures.

F. Ozel, ApJ. 693:1775, (2009).



•Solutions of GR equations for different EoS's

•M(R) deduced assuming "touchdown" occurs at peak luminosity

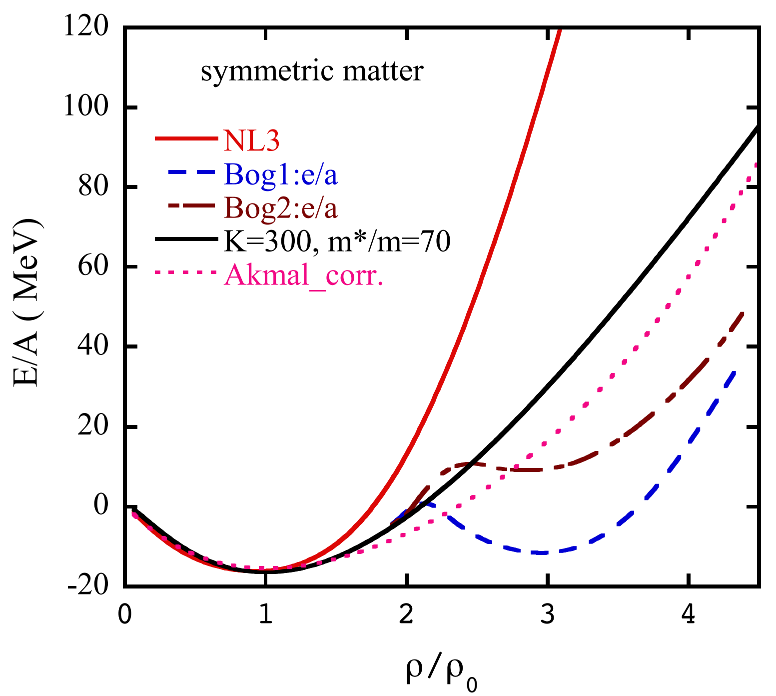
- Steiner et al., ApJ 722, 33 extract small radii, consistent with Ozel, and soft neutron matter EoS.

Suleimanov et al, ApJ 742, 122 in an analysis of the full time dependence extract ~ 14 km radii consistent with stiffer neutron matter EoS

⇒ It is important to obtain laboratory constraints.

Why not just use the frequency of monopole resonance? -need for laboratory probes sensitive to higher densities.

- In a Taylor series about ρ_0, the incompressibility, K_{nm} provides the term proportional to $(\rho-\rho_0)^2$.
- The solid black, dashed brown and dashed blue EoS's all have K_{nm}=300 MeV.
  - To probe the EoS at $3\rho_0$, you need to compress matter to $3\rho_0$ to determine the higher order terms.



- Observables
  - Giant monopoles resonance constrains curvature about minimum K=240 ± 5 MeV.
  - Higher density can be achieved momentarily in nucleus-nucleus collisions:
    - Collective flow.
    - Kaon production

Flow studies of the symmetric matter EOS

- Theoretical tool: transport theory:
  - Example Boltzmann-Uehling-Uhlenbeck eq. (Bertsch Phys. Rep. 160, 189 (1988).) has derivation from Time Dependent Hartree Fock (TDHF):

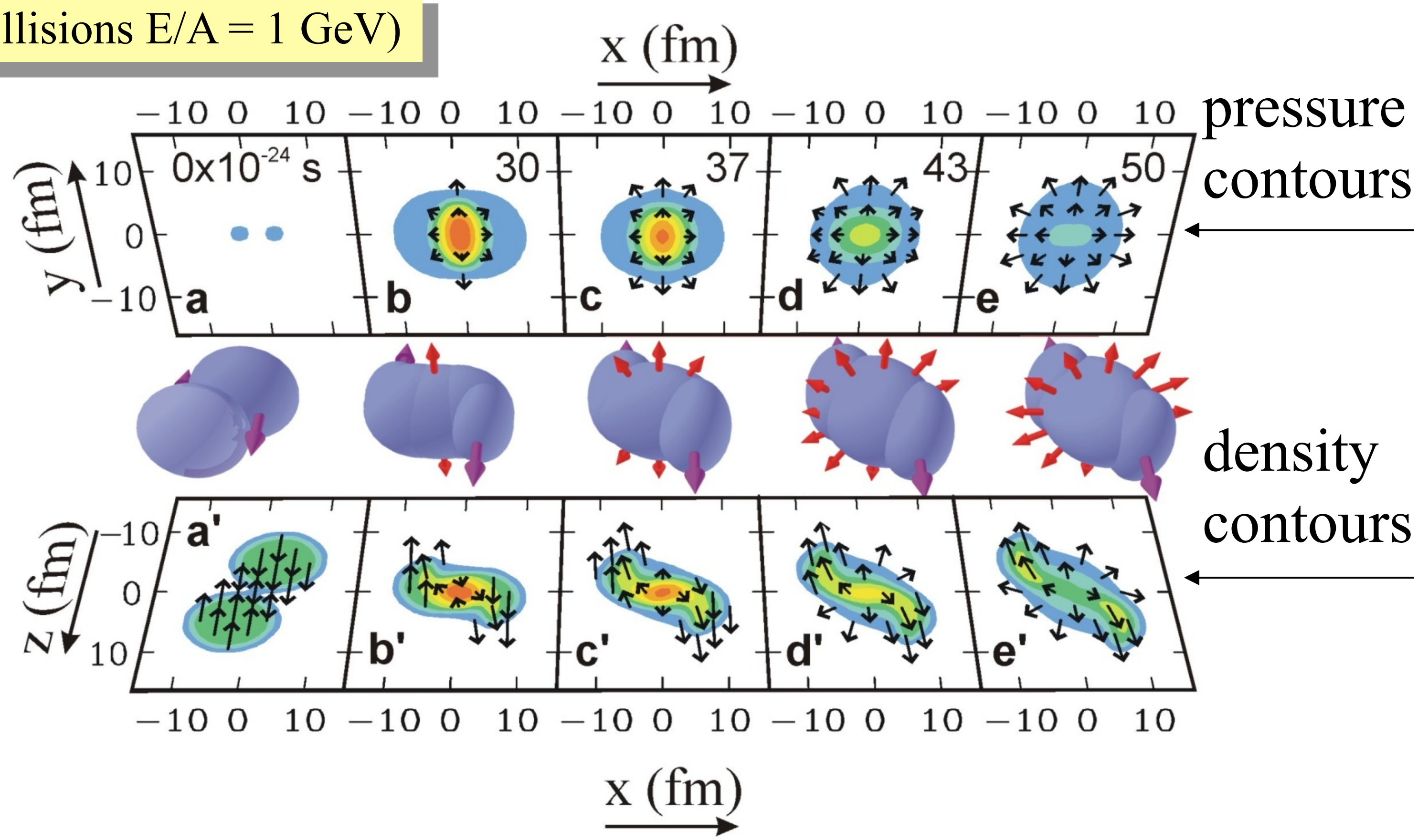
$$\frac{\partial f_1}{\partial t} + \mathbf{v} \cdot \nabla_{\mathbf{r}} f_1 - \nabla_{\mathbf{r}} U \cdot \nabla_{\mathbf{p}} f_1$$

$$= \frac{4}{(2\pi)^3} \int d^3k_2 d\Omega \frac{d\sigma_{nn}}{d\Omega} v_{12} \left[f_3 f_4 (1 - f_1)(1 - f_2) - f_1 f_2 (1 - f_3)(1 - f_4) \right]$$

    - f is the Wigner transform of the one-body density matrix
    - semi-classically, $= f(r, p, t)$ (number of nucleons/d^3rd^3p at r and p).
    - BUU can describe nucleon flows, the nucleation of weakly bound light particles and the production of nucleon resonances.
  - The production of heavier fragments is difficult problem, but can be approximately modeled with Anti-Symmetrized Molecular Dynamics (AMD) and other molecular dynamics techniques .
  - The most accurately predicted observables are those that can be calculated from $f(r, p, t)$ i.e. flows and other average properties of the events.

Constraining the EOS at higher densities by nuclear collisions

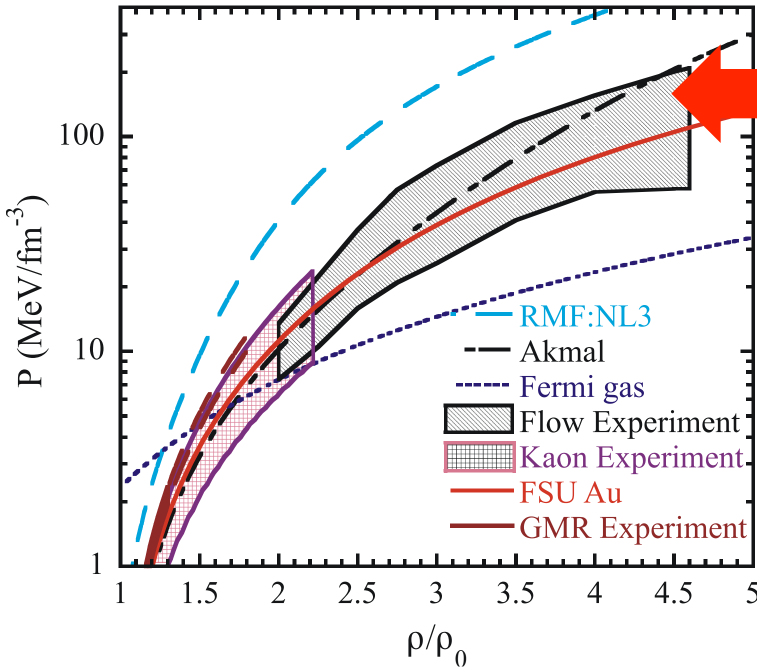
Au+Au collisions E/A = 1 GeV)



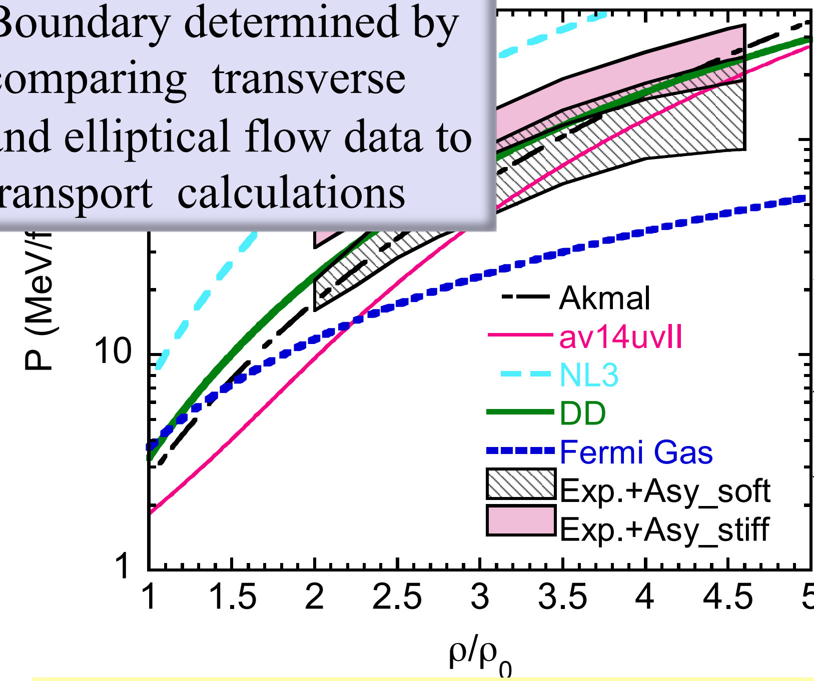
- Two observable consequences of the high pressures that are formed:
  - Nucleons deflected sideways in the reaction plane.
  - Nucleons are “squeezed out” above and below the reaction plane. .

Example: Flow Constraints on symmetric matter EOS at $\rho > 2\rho_0$.

$E/A(\rho, \delta) = E/A(\rho, 0) + \delta^2 \cdot S(\rho)$ $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A \approx 1$



Boundary determined by comparing transverse and elliptical flow data to transport calculations

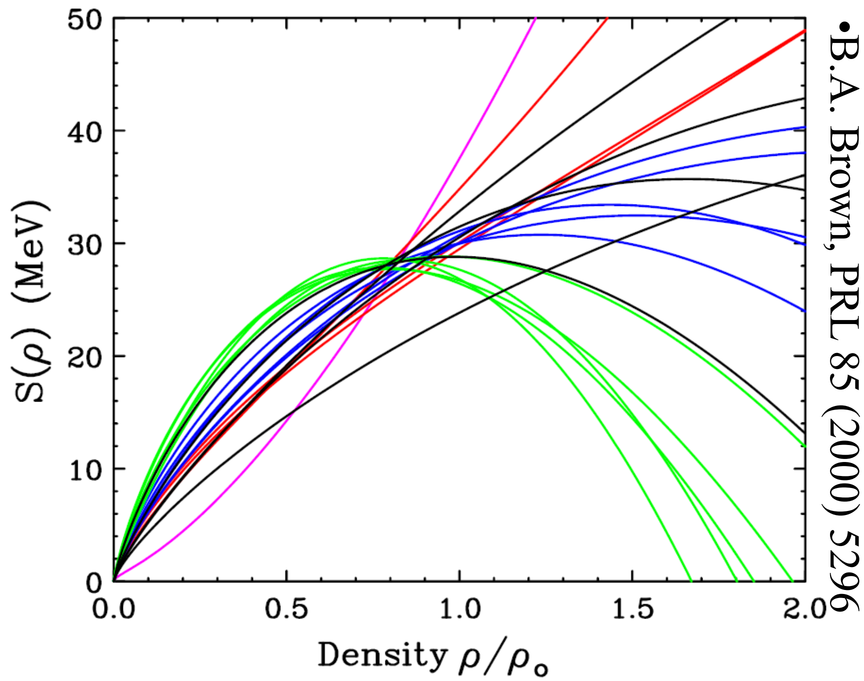


Danielewicz et al., Science 298,1592 (2002).

- Flow confirms the softening of the EOS at high density.
- Constraints from kaon production are consistent with the flow constraints and bridge gap to GMR constraints.
- Note: analysis requires additional constraints on m* and σ_{NN}.

- The symmetry energy dominates the uncertainty in the n-matter EOS.
- Improved laboratory constraints on the density dependence of the symmetry energy are a key objective..

Constraining the symmetry energy at sub-saturation densities



L and S_0 govern the phenomena

$$S(\rho) = S_o + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \ldots$$

$$L = 3\rho_0 \left.\frac{\partial S(\rho)}{\partial \rho}\right|_{\rho=\rho_0} = \frac{3}{\rho_0} P_{sym}$$

- In a neutron-rich system, the symmetry energy attracts protons and repels neutrons
- Observables that can probe sub-saturation densities:
  - Isospin diffusion:
  - Neutron-proton spectra and flows.
  - Difference between neutron and proton matter radii.
  - Giant and pygmy dipole resonances
  - El dipole polarizability
  - Nuclear binding energies and isobaric analog resonance energies.

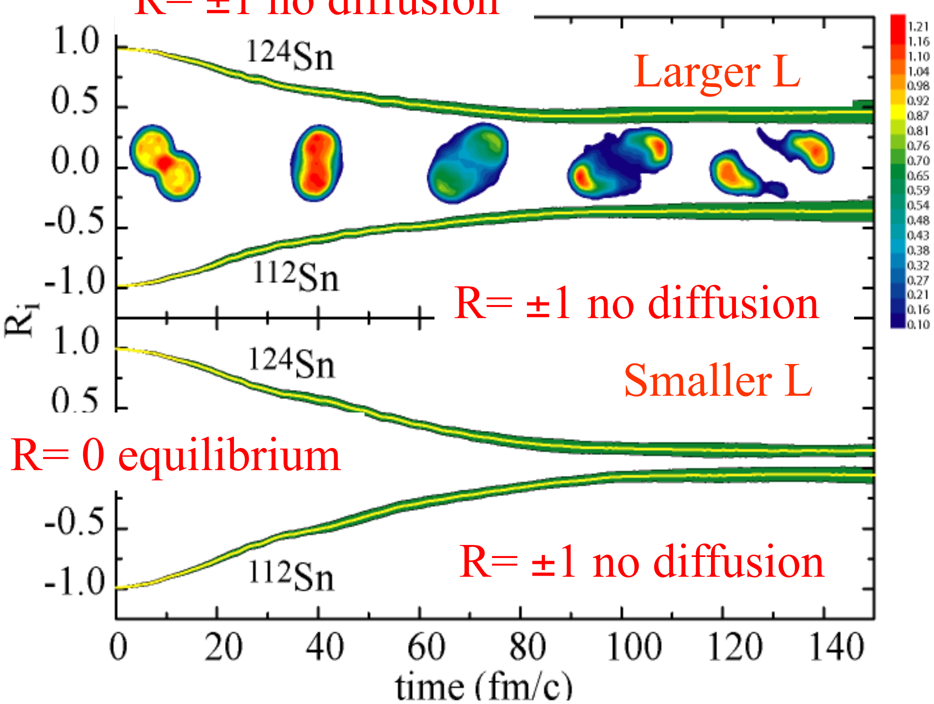
Probe: Isospin diffusion in peripheral collisions

- Collide projectiles and targets of differing isospin asymmetry
- Probe the asymmetry $\delta=(N-Z)/(N+Z)$ of the projectile spectator during the collision.

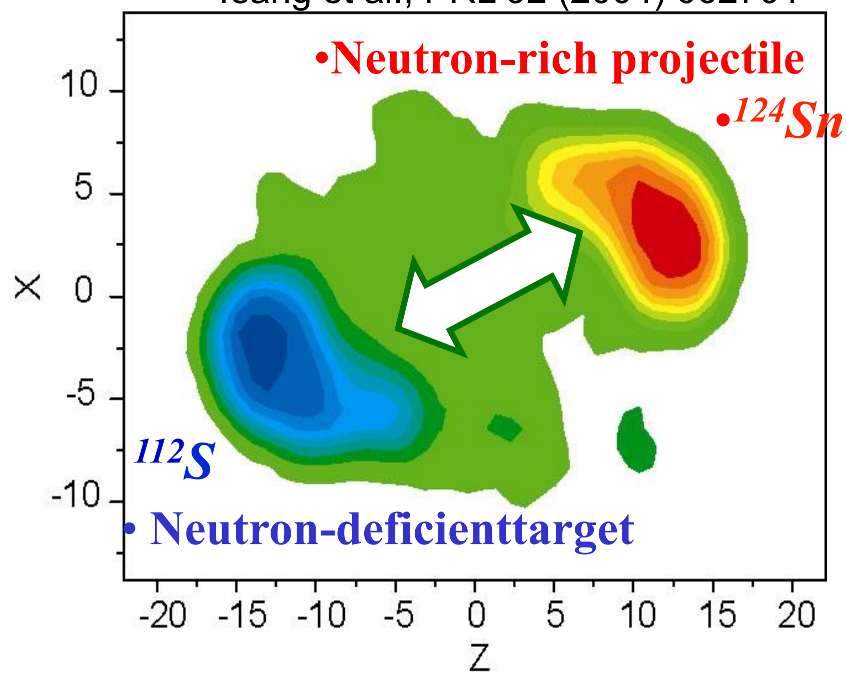
$$R_i(\delta) = 2 \cdot \frac{\delta - (\delta_{both\_neut.-rich} + \delta_{both\_prot.-rich})/2}{\delta_{both\_neut.-rich} - \delta_{both\_prot.-rich}}$$

Systems: mixed $^{124}Sn+^{112}Sn$, n-rich $^{124}Sn+^{124}Sn$, p-rich $^{112}Sn+^{112}Sn$

R= ±1 no diffusion



•Tsang et al., PRL 92 (2004) 062701



measure asymmetry after collision

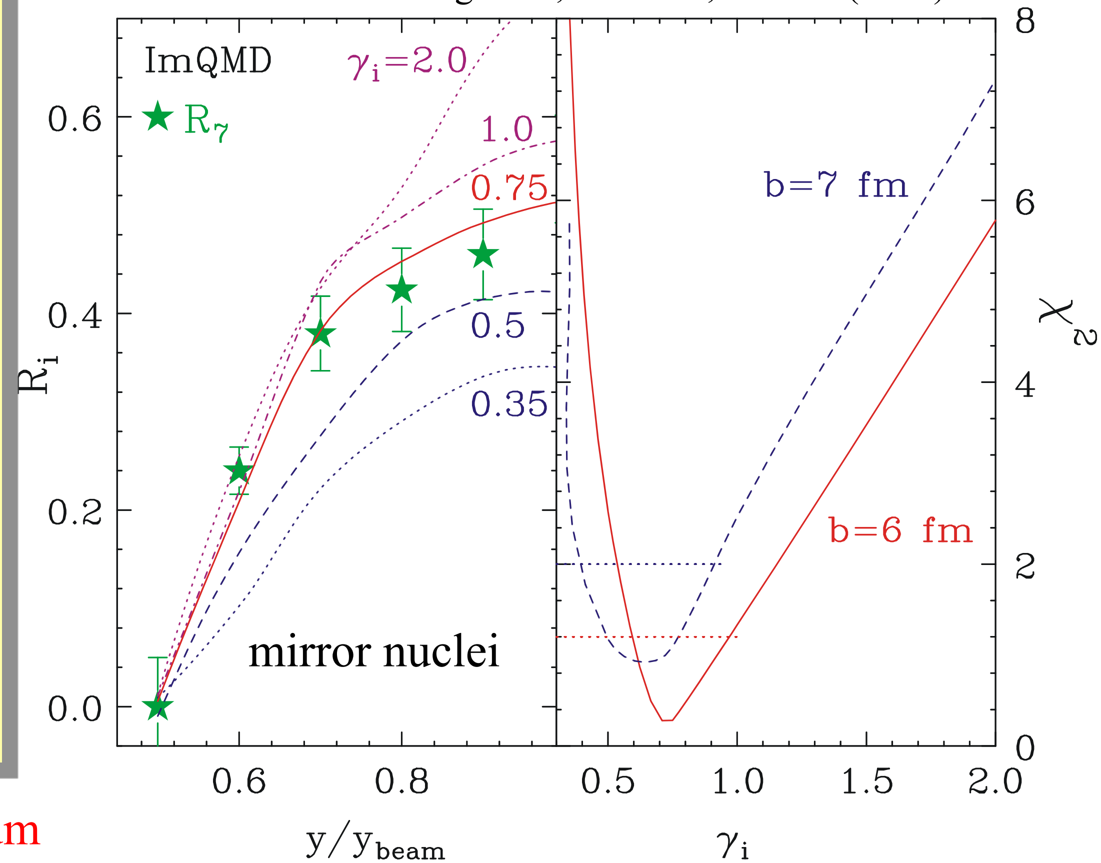
Comparison to QMD calculations

(Yinxun Zhang and Zhuxia Li)

- ImQMD calculations were performed for γ_i=0.35-2.0, S_{int}=17.6 MeV.
- Momentum dependent mean fields with $m_n^*/m_n = m_p^*/m_p = 0.7$ were used. Symmetry energies: $S(\rho) \approx 12.3\cdot(\rho/\rho_0)^{2/3} + 17.6\cdot(\rho/\rho_0)^{\gamma_i}$

- Experiment samples a range of impact parameters
  - b≈5.8-7.2 fm.
  - larger b, smaller γ_i
  - smaller b, larger γ_i
- 2 observables provide R(δ)
  - R_α - changes in isotope distribution
  - R_7 - changes in ratios of A=7 mirror nuclei

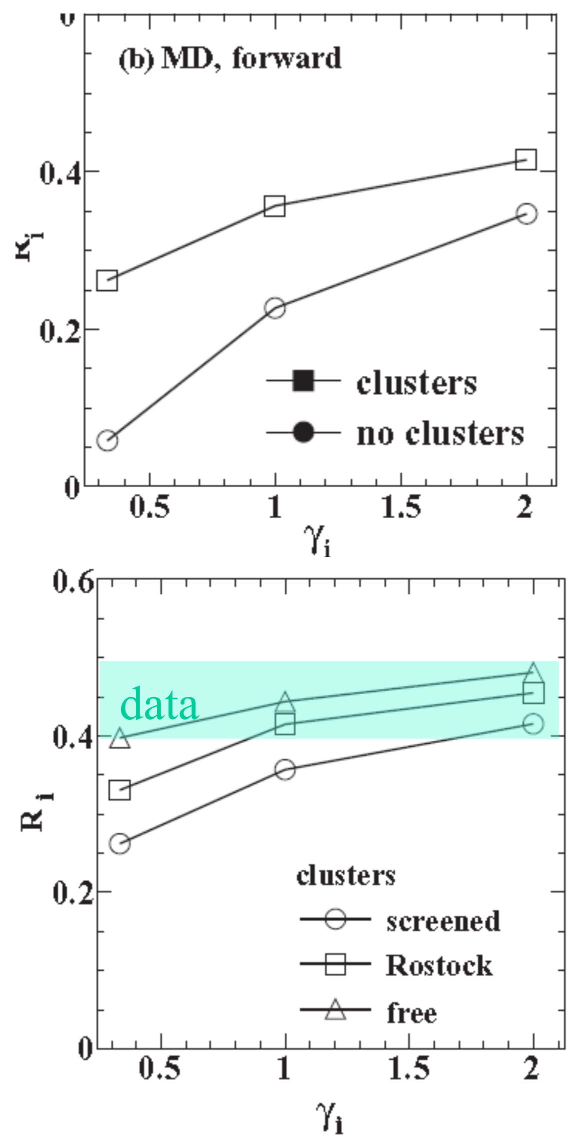
Tsang et al., PRL 102, 122701 (2009).



R= ±1 no diffusion   R= 0 equilibrium

BUU vs. QMD – role of clusters?

- BUU with same symmetry energy predicts more diffusion.
  - Constraints obtained with BUU interpretation overlapped the QMD constraints but favor stiffer symmetry energy. (Li and Chen, PRC 72, 064611 (2005))
- What may be the influence of cluster production?
  - Test using approach of Danielewicz and Bertsch, NPA 533, (1991).
  - Coalescence heating of system magnifies the role of collisions
  - Cluster production diminishes diffusion similar to trend of the IM_QMD.

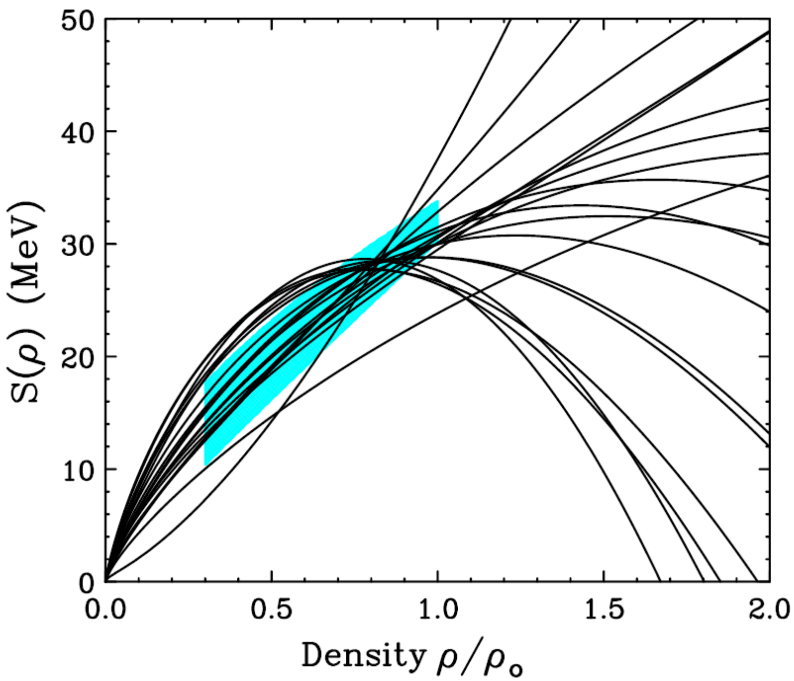


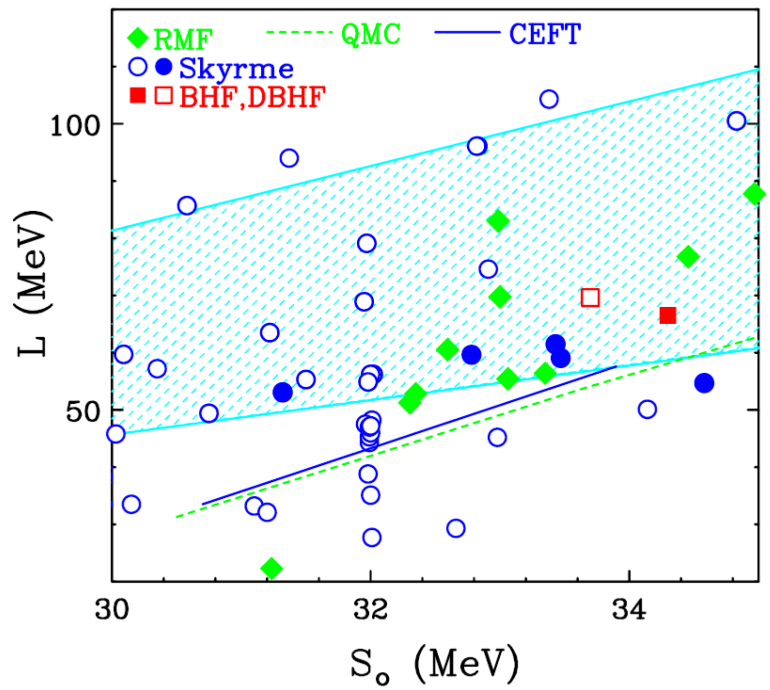
Coupland et al, PRC 84, 054603 (2011)

Constraints from isospin diffusion and n/p spectra

$S(\rho)=12.5(\rho/\rho_o)^{2/3}+(S_0-12.5)\cdot(\rho/\rho_o)^{\gamma}\ ;\ 0\le\gamma\le1$

M.B Tsang et al., arXiv:1204.0466



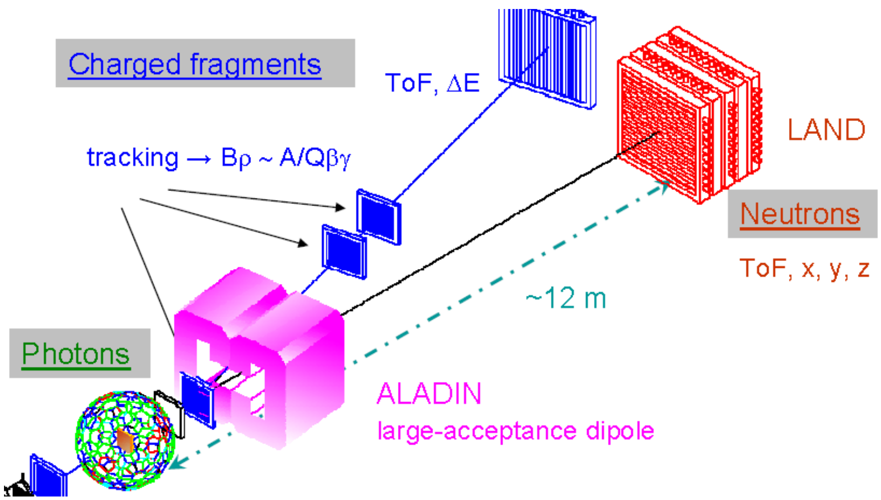


- These constraints reduce the range of possible density dependencies.
- Some possible Skyrme interactions can be ruled out.

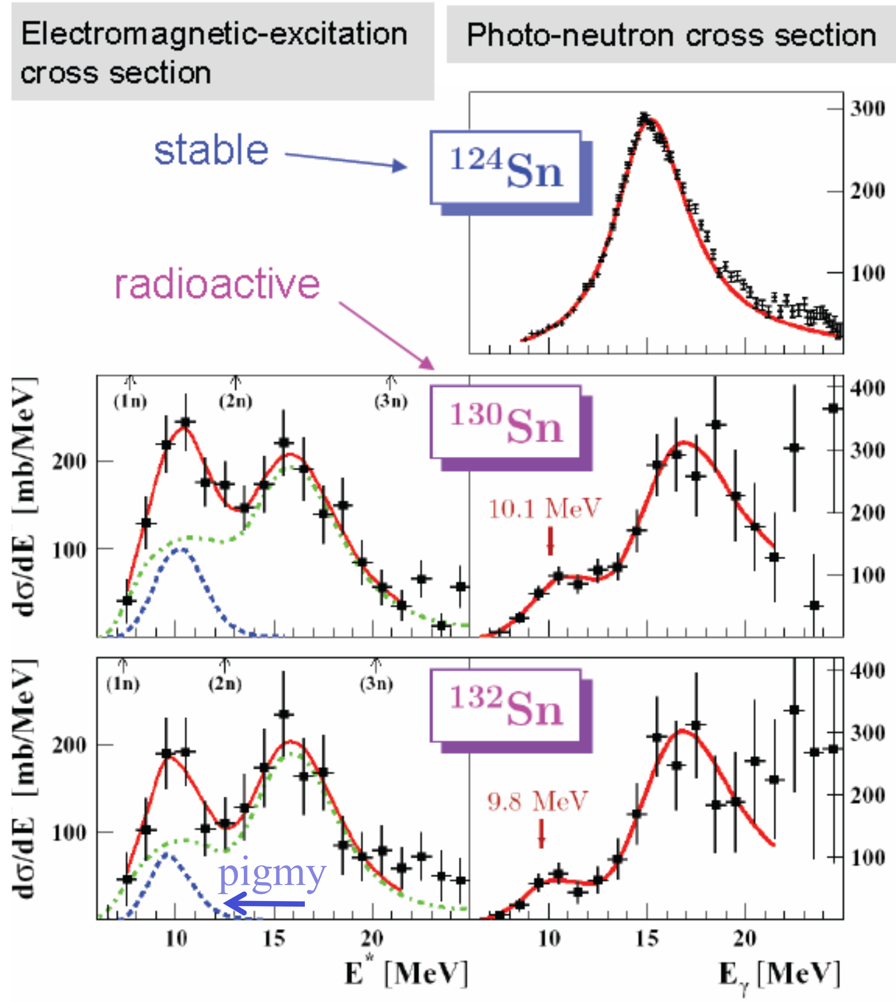
$$S(\rho)=S_o+\frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right)+\frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2+\ldots$$

$$L=3\rho_0\left.\frac{\partial S(\rho)}{\partial\rho}\right|_{\rho=\rho_0}=\frac{3}{\rho_0}P_{sym}$$

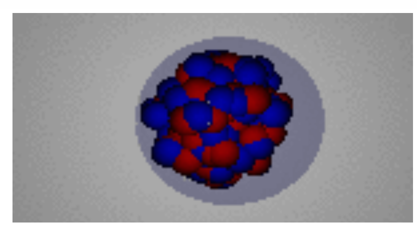
PDR: Electric dipole excitations of the neutron skin



- Coulomb excitation of very neutron rich ^{130,132}Sn isotopes reveals a peak at $E^{*} \approx 10$ MeV.
  – not present for stable isotopes
- Consistent with low-lying electric dipole strength.
- calculations suggest an oscillation of a neutron skin relative to the core.

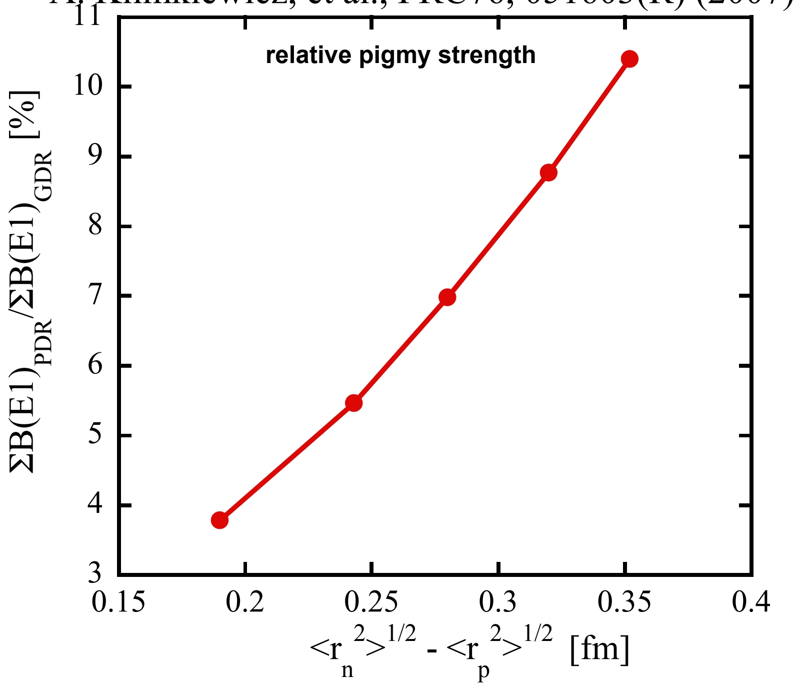


P. Adrich et al., PRL 95 (2005) 132501

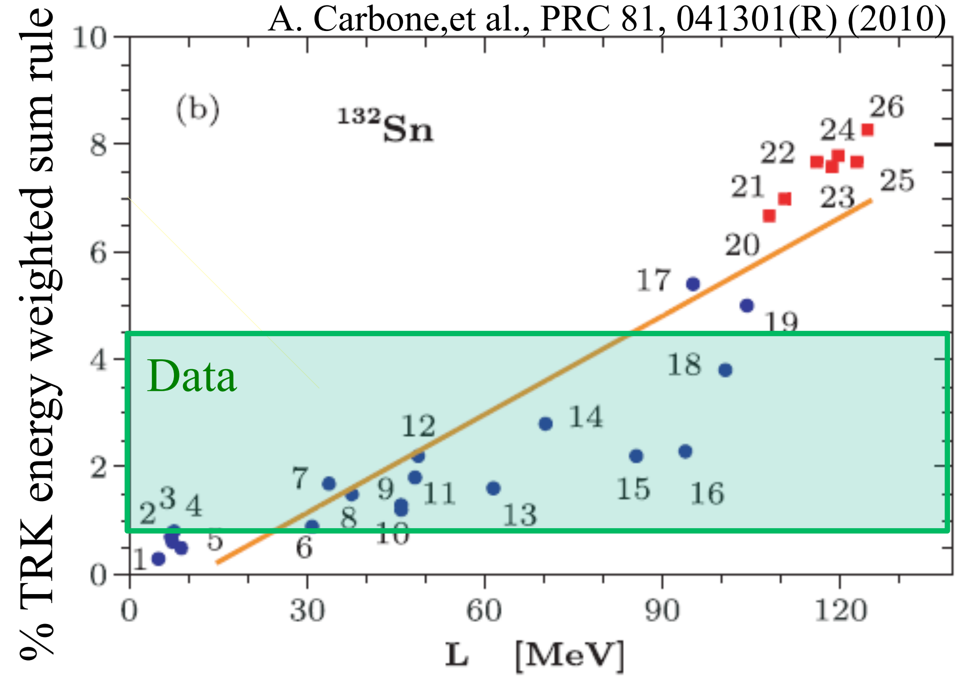


Relation to symmetry energy

A. Klimkiewicz, et al., PRC76, 051603(R) (2007)



A. Carbone,et al., PRC 81, 041301(R) (2010)



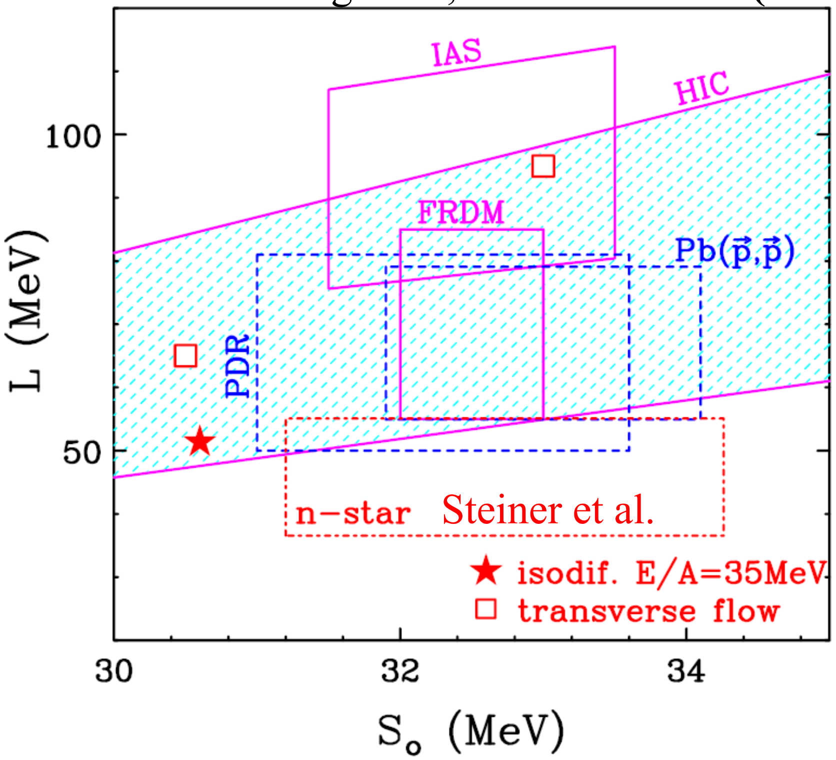
- Random phase approximation (RPA) calculations show a strong correlation between the neutron - proton radius difference and the fractional strength in the pygmy dipole resonance.

- Random phase approximation (RPA) calculations show a strong correlation between the fractional strength and

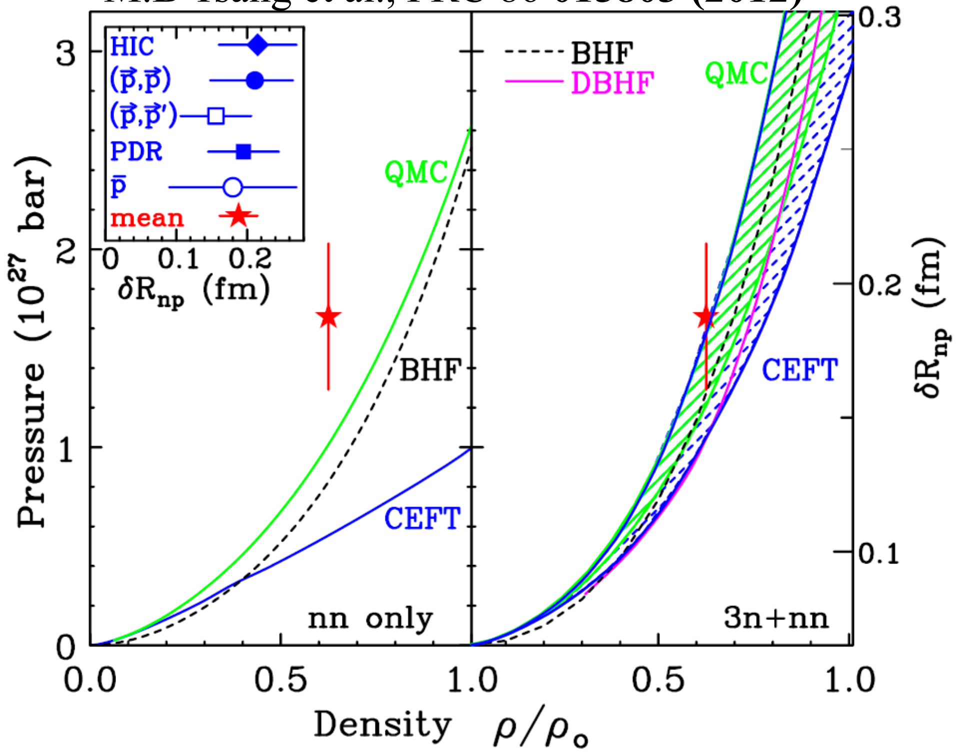
$$L = 3\rho_0 \left.\frac{\partial E_{sym}}{\partial \rho_B}\right|_{\rho_B=\rho_0} = \frac{3}{\rho_0} P_{sym}(\rho_0)$$

Status of constraints at sub-saturation densities

M.B Tsang et al., PRC 86 **015803 (2012)**



M.B Tsang et al., PRC 86 **015803 (2012)**

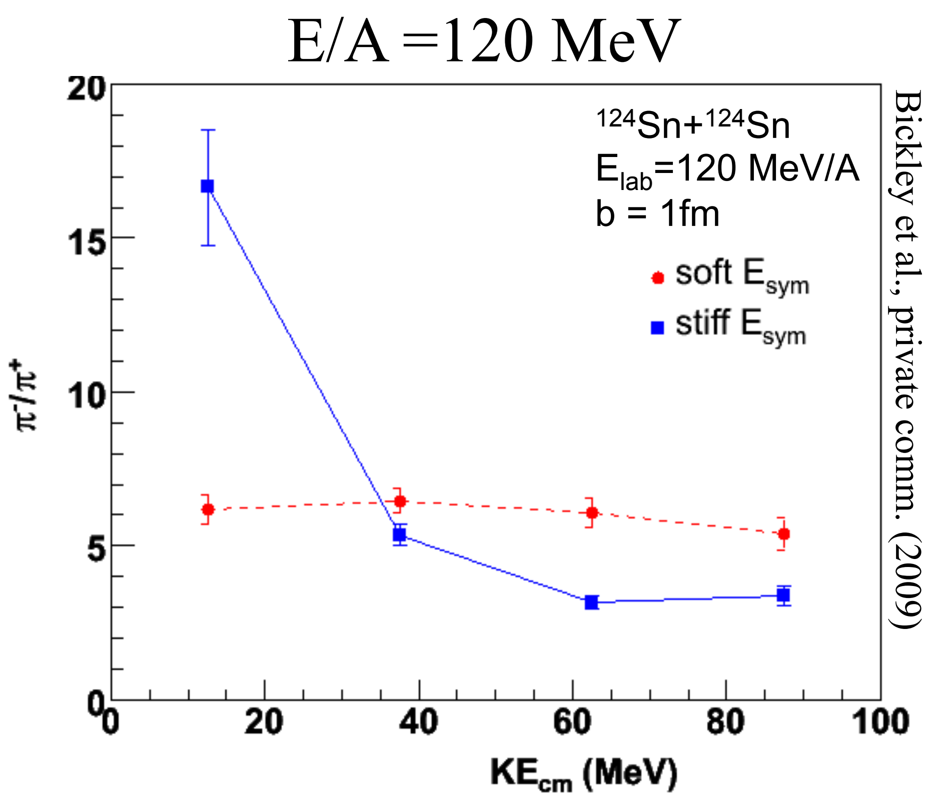


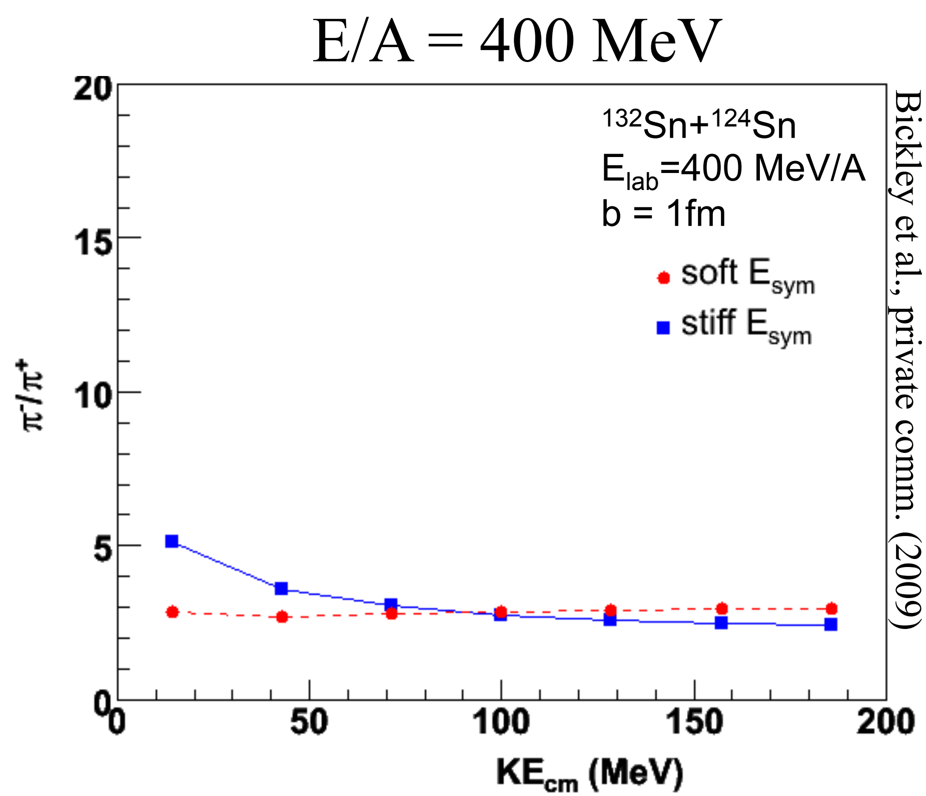
- Current laboratory constraints on the symmetry energy at sub-saturation density are roughly consistent but need to be more stringent.
- Include constraints from neutrons star analyses that suggest small neutron star radii and lower symmetry pressures at saturation densities,.
- Calculations involving “realistic” two body forces suggest that 3-neutron forces may be required to reproduce the laboratory trends.

Objective for N-N collisions: Constraints on symmetry energy at $\rho>\rho_0$. (experimentalist prospective)

- Laboratory constraints can ***only*** come from nucleus-nucleus collisions.
- Promising observables :
  - comparisons of neutron and proton spectra and flows.
  - comparisons of positive and negative pion production and flows.
- International collaboration has been formed and is planning experiments:
  - ongoing comparison of n-p spectra and flows (ASYEOS experiment at GSI).
  - future comparisons of positive and negative pions and also n-p spectra and flows at RIKEN. (SAMURAI TPC project: DOE FOA)
  - future comparisons of positive and negative pions at CCF and FRIB. (AT-TPC project: NSF MRI)

Sensitivity of pion production to the symmetry energy





- Pion ratio shows stronger dependence on the symmetry energy at low incident energies and low pion energies.
  – Searching for even more sensitive pion observables.
- Building TPC's to measures at both energies: E/A<200 MeV at MSU and E/A=300-350 MeV at RIKEN.

BUU from: Danielewicz, NPA**673**, 375 (2000).

Nuclear Symmetry Energy (NuSym) collaboration

http://groups.nscl.msu.edu/hira/sep.htm

- MSU: B. Tsang & W. Lynch, G. Westfall, P. Danielewicz, E. Brown, A. Steiner
- Texas A&M University : Sherry Yennello, Alan McIntosh
- Western Michigan University : Michael Famiano
- RIKEN, JP: TadaAki Isobe, Atsushi Taketani, Hiroshi Sakurai
- Kyoto University: Tetsuya Murakami
- Tohoku University: Akira Ono
- GSI, Germany: Wolfgang Trautmann , Yvonne Leifels
- Daresbury Laboratory, UK: Roy Lemmon
- INFN LNS, Italy: Giuseppe Verde, Paulo Russotto
- GANIL, France: Abdou Chbihi
- CIAE, PU, CAS, China: Yingxun Zhang, Zhuxia Li, Fei Lu, Y.G. Ma, W. Tian
- Korea University, Korea: Byungsik Hong

Summary and Outlook

- The density dependence of the symmetry energy is of fundamental importance to the understanding neutron stars.
- Heavy ion collisions provide unique possibilities to probe the EOS of dense asymmetric matter.
- Calculations suggest a number of promising observables that can probe the density dependence of the symmetry energy.
  - Isospin diffusion, n/p spectral ratios, mass, IAS's, GMR, Pigmy and Giant Dipole resonances provide some constraints at $\rho \leq \rho_0$.
  - π^+ vs. π^- production, neutron/proton spectra and flows may provide constraints at $\rho \approx 2\rho_0$ and above.
- Presently, the most promising observables are the ones that can calculated via the BUU transport theory.
- The availability of fast stable and rare isotope beams at a variety of energies at FRIB, RIKEN and GSI allows the exploration of the symmetry energy at a range of densities.